EVALUATION AND PREDICTION OF LONG-TERM SPACE ENVIRONMENTAL EFFECTS ON NON-METALLIC MATERIALS

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by

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I. INTRODUCTION

The objective of this program is to determine the effects of prolonged space environment on a variety of spacecraft materials and where possible, compare these results with predicted behavior.

II. TECHNICAL PROGRESS SUMMARY

Task I - Physical properties testing

Peel strength tests not previously reported for a general purpose epoxy adhesive(EC-2216) are tabulated as a part of this report.

The first series of irradiation tests were conducted at MSFC-Huntsville and returned to MMC for testing. The test results before and after irradiation with Mev electrons are reported for the following materials:

Hysol C7-4248 Epoxy Resin	Electrical Properties
DC 93-500 Silicone Encapsulant	" "
Vespel SP-1, Polyimide Sheet	" "
Nylon	Tensile Properties
Polyurethane	"
Lexan	"
Lucite	"

It should be noted that the Lucite specimens could not be tested after irradiation due to their embrittled condition.

Specimens for the second series of irradiation experiments were selected and transported to MSFC in two cannisters. Cannister No. 1 contains lap shear specimens exclusively for the evaluation of various adhesives identified as HT 435, HT 424, FM 96 U, and EA 934. All lap shear specimens are constructed 2014-T6 aluminum tabs of .063" thickness. Three replicates of each material are included. Cannister No. 2 contains 3 replicates(dogbone tensile) of Vespel SP-1, a single tensile specimen for Lucite, Nylon, Lexan, and Polyurethane materials, 3 replicates(2" diameter discs) of Ecco-Foam FPH, and 3 peel specimens of EC 2216. The latter material was briefly air exposed to reduce the length of each specimen by shearing.

Task III. Compilation, analysis and documentation of environmental effects

The final draft of Item 3.1 Literature Survey is included with this report for review and comments prior to its inclusion as Appendix A of the Final Report.

III. WORK PLANNED FOR NEXT MONTH

1. Conduct TGA/RGA analyses of specimens from the first irradiation series.
2. Transfer graphite/epoxy specimens from the vacuum chamber at MSFC and transport them to MMC.
3. Initiate testing of all samples returned from MSFC.

#EC-2216 General Purpose Epoxy Adhesive(3M)
Lot No. 28 BIR

180° Peel Strength (ASTM D-903)

Exposure	Peel Strength (lb/in)			
	Average	High	Low	No. Samples Tested
Baseline	37	44	26	10
Heat Compatibility (1)	.51	56	45	9
Heat Compatibility (1) plus Thermal Cycling (2)	48	53	42	3
Heat Compatibility (1) plus Thermal Cycling (2) plus 100 months Thermal Vacuum (3)	19	26	7	5

(1) Heat Compatibility - 571 hours at 275°F(408°K) in N_2 atmosphere.

(2) Cycled 40 times between -50°F and 150°F with a 1 to 16-hour hold at each temperature.

(3) Tested at 10^{-5} torr after exposure at 150°F (338°K) and 10^{-6} torr for the specified length of time.

Hysol C7-4248 Epoxy Resin*

Exposure	Dielectric Constant	Dissipation Factor
Before Irradiation with Mev electrons, Heat Compatibility(1) plus 100-month Thermal Vacuum Exposure(2)	3.007 3.123 Average = 3.065	.0047 .0122 .0084
After Irradiation	3.238	.0047

* Cure cycle - 6 hours at 300°F.

(1) Heat Compatibility - 385 hours at 300°F(433°K) in N_2 atmosphere.

(2) Tested per ASTM-D-150 at 1 X 10^{-5} torr after exposure for specified length of time at 150°F (338°K) and 1 X 10^{-6} torr.

Vespel SP-1, Polyimide 0.060" Sheet
(E. I. Dupont deNemours & Co.)

Exposure	Dielectric Constant*			Dissipation Factor*		
	Average	High	Low	Average	High	Low
Baseline	2.94	2.98	2.84	.00046	.00047	.00046
Heat Compatibility (1) Plus 1 Mo, Thermal Vacuum Exposure (2)	2.87	2.92	2.84	.00016	.00016	.00015
BEFORE IRRADIATION						
Heat Compatibility (1) Plus 100-Month Thermal Vacuum Exposure	2.40	2.51	2.35	.00140	.00200	.00110
AFTER IRRADIATION(Mev e^-)	2.52	2.68	2.43	.00240	.00420	.00100

* 3 specimens per condition tested in accordance with ASTM-D-150 procedures.

(1) Heat compatibility - 570 hours at 275°F(408°K) in N_2 atmosphere.

(2) Tested at $1_6 X\ 10^{-5}$ torr after exposure for the specified length of time at 150°F(338°K) and $1 X 10^{-6}$ torr.

DC 93-500 Silicone Elastomeric Electrical Encapsulant*
(Dow-Corning Batch No. 001091)

Exposure	Dielectric Constant			Dissipation Factor		
	Average	High	Low	Average	High	Low
Baseline	2.79	2.81	2.78			
Heat Compatibility (1)	2.76	2.78	2.74			
Heat Compatibility (1) Plus 1100-hour Thermal Vacuum exposure (2)	2.76	2.84	2.68			
BEFORE IRRADIATION						
Heat Compatibility (1) Plus 100 Month Thermal Vacuum exposure (2)	2.700	2.742	2.649	.0043	.0077	.0018
AFTER IRRADIATION(Mev e^-)	1.985	Single Specimen		.0026	Single Specimen	

*Cured 24 hours at room temperature plus 4 hours at 65°C(338°K).

(1) Heat Compatibility - 379 hours at 275°F(408°K) in N_2 atmosphere.

(2) Tested per ASTM-D-150 at $1 X 10^{-5}$ torr after exposure for specified length of time at 150°F(338°K) and $1 X 10^{-6}$ torr.

TENSILE PROPERTIES - FIRST IRRADIATION SERIES

Material/ Condition	Specimen No.		Ultimate Tensile Strength (lb/in^2)	Percent Elongation in 1.5" (at failure)
NYLON				
Before Irrad/ Mev electrons	061		11,100	50
	062		11,300	37
	063		11,200	8
		Average	11,200	32
After Irrad.	065		12,700	28
	066		12,800	28
	067		12,700	23
		Average	12,730	26
POLYURETHANE*				
Before Irrad/ Mev electrons	114		7,780	1200
	115		8,610	1253
	116		8,075	1227
	117		7,680	1200
		Average	8,036	1220
After Irrad.	118		7,100	893
	119		6,700	893
	120		6,800	906
		Average	6,870	897
LEXAN				
Before Irrad/ Mev electrons	084		8,575	145
	085		8,500	87
	086		8,485	15
	087		8,450	38
		Average	8,503	71
After Irrad.	088		8,875	60
	089		8,694	93
	090		8,897	93
		Average	8,822	82
LUCITE				
Before Irrad/ Mev electrons	097		11,500	8
	098		11,430	10
	099		11,160	9
	100		10,750	8
		Average	11,210	9
After Irrad.	102 103 104	Crazed, discolored(straw to light brown), cracked and/or broken during removal from irradiation specimen holder - the latter apparently due to embrittled condition.		

* Cross-head speed= 2"/minute. All others tested at ½"/minute. Specimen dimensions were ½" width X 1½" reduced section length except polyurethane specimens which were ¼" in reduced section width.

FINAL DRAFT

EVALUATION AND PREDICTION OF LONG-TERM SPACE ENVIRONMENTAL EFFECTS ON NONMETALLIC MATERIALS

Contract NAS8-33578

APPENDIX A

LITERATURE SEARCH

by

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A computer-assisted literature search was carried out in the NASA and DOD data banks for space environmental effects on the three types of spacecraft materials specified by the COR. The materials chosen by the COR were Kapton, Teflon, and silicones, including the S-13 and S-13G paints. The information developed includes flight data as well as laboratory test data. The search developed 132 references of which approximately 70 were surveyed for the three subject materials.

Significant quantities of information were obtained from three sources. A large amount of laboratory data on chemical and physical properties was developed by Martin Marietta Denver Aerospace during the Viking project and compiled into a handbook. Pertinent pages from this handbook are referenced in the appropriate sections. Boeing Aerospace conducted extensive irradiation studies of thermal control coatings during the 1965-1966 period. Much of their information on S-13 and S-13G will also be referred to later. An extensive report by TRW, Properties of Metalized Flexible Materials in the Space Environment, was published in 1978. It contains much information on Teflon and Kapton and will be referred to in the appropriate paragraphs. Other reports and compilations will also be discussed; however, references within compilations will not be referred to as they can be found in the particular compilation.

A. SILICONES AND THE S-13 AND S-13G THERMAL CONTROL PAINTS

1. Silicones

Because silicones do not contain the variety of secondary additives common to most organics, thermal-vacuum exposure does not significantly alter their physical and electrical properties. Dimethyl silicones display greater stability to ultraviolet degradation than the phenyl-containing silicones, which is the opposite behavior of particle radiation stability. The photon-irradiated phenyl-based materials show measurable surface effects of cracking, crazing, and discoloration. However, low-temperature (-90°C flexibility) properties are imparted to silicone elastomers by a small but optimum number of phenyl groups. The more bulky phenyl groups break up the regularity of the polymethylsiloxane chain necessary for crystallitic growth. Particle irradiation in high doses (10 to 100 megarads) causes increased hardness and tensile strength and appreciably reduces elongation of silicone elastomers. The higher phenyl-containing elastomers are more resistant to such effects.[1]

A recent compilation[2] of VCM (vacuum-condensible materials) data shows silicone rubbers to sustain a TML (total weight loss) ranging between 0.1 to 3.5% and a VCM ranging from 0.00 to 0.6% when exposed to thermal-vacuum for 24 hours at 125°C under 10^{-6} torr vacuum.

The thermal decompositions in vacuum follow[3,4] simple first-order kinetics with the rate equation given by

$$\frac{dx}{dt} = k_T(a_o - x)$$

where k_T is the rate constant at temperature T, dx/dt is the rate of weight loss, and a_o-x is the concentration and a_o is the initial concentration. It has been shown that the same rate equations hold for decompositions in air.[5]

The activation energies for thermal decomposition of silicones in vacuum do not exceed about 30 kcal. This can be ascertained from the pages from the Martin Marietta handbook[4] of Viking data referenced in the following tabulation.

Material	Pages (Inclusive)
Cho-Seal 1224	S-1 - S-9
DC6-1102	S-10 - S-13
DC6-1104	S-14 - S-17
DC6-1106	S-19 - S-22
DC92-007	S-23 - S-28
DC93-500	S-29 - S-33
MS40G08	S-34 - S-37
Silicone Tape, Series 600	S-38 - S-42
RTV-511, Modified	S-43 - S-48
ZP5044 Silicone Gasket	S-49 - S-52

As mentioned earlier, the effect of thermal-vacuum exposure on the physical properties of silicones is expected to be slight as shown by the Viking data referenced above. Concordant with these data are the results [1] for a test of Young's modulus in flexure stiffening temperature (stiffening temperature defined as the point where Young's modulus reaches 10000 psi). A general-purpose silicone RTV and a clear rubbery-resinous silicone showed no change in the stiffening temperature after exposure for one week at 150°C under 10^{-7} torr vacuum.

Laboratory studies[6] of ultraviolet irradiation have shown that only the polydimethylosiloxanes (RTV-615 and O-I type 650) are resistant to degradation when exposed to solar radiation. After 600 ESh (equivalent solar hours) there was no significant degradation with $\Delta\alpha_s$ = 0.005 to 0.008. The SR series all degraded by 100 ESh with $\Delta\alpha_s$ = 0.044 to 0.091. A test sample of methyl silicone was flown[7] on OSO-III along with samples of thermal control coatings. Over approximately 2700 ESH, α_s changed by 0.11 but there was no apparent change up to about 200 ESH.

The decrease in transmittance over the wavelength range 0.4 to 2.5 μ of DC 93-009 under proton irradiation has been studied.(8) For 150-keV protons at irradiation rates between 6.6 x 10^{10} and 6.6 x 10^{13} protons/cm²/s, the transmittance is given by

$T = 11.7\,E^{-0.134}$

within 2% for total energy, E, deposited between 10^{5} and 10^{10} ergs/cm². For 50-keV protons at rates of 6.6 x 10^{11} and 6.6 x 10^{13} protons/cm²/s,

$T = 5.2\,E^{-0.0935}$

over the same total deposited energy.

2. S-13 and S-136 Thermal Control Paints

a. Ultraviolet Radiation - Through 1966 an experiment on OSO-II provided the most extensive data for thermal coatings on a near-earth satellite.(9) At that time the changes in α_s were attributed to changes in the near-infrared reflectance. That this is indeed the case is shown in Figure A-1 taken from the extensive report of the Boeing group.(10) The recovery shown in the figure occurs after backfilling the vacuum irradiation chamber with dry air. Some changes in α_s have been collected in Table A-1.

The large changes in α_s on the Skylab experiment have been attributed to a combination of contamination and solar degradation.(11) The OSO-III results are in good agreement with OSO-II as well as Pegasus I results, but the changes in α_s are much less than for Mariner V and the difference is attributed(7) to solar wind effects on Mariner V.

The Boeing group has done extensive work(10) on electromagnetic and particle radiation on S-13 and S-136-type coatings. For ultraviolet [illegible] used both mercury arc (four Gates and two [illegible]) and xenon long-arc sources. With S-13 the xenon source showed much more damage (changes in reflectance through the wavelength range 0.2 to 2.5 μ) for 65 ESH than 135 ESH of the mercury arc. Only between 0.4 and 0.5 μ is the buildup greater with the 135 ESH of the mercury source. Significant reflection losses occur in both S-13 and S-136. Figures A-2 and A-3 show these changes.(10) The S-136, which undergoes smaller changes in the IR, exhibited little recovery even after seven days of backfilled air in the vacuum irradiation chamber. The S-13 had nearly complete recovery (Fig. A-1). In the visible region S-136 showed no recovery and S-13 only a slow partial recovery.

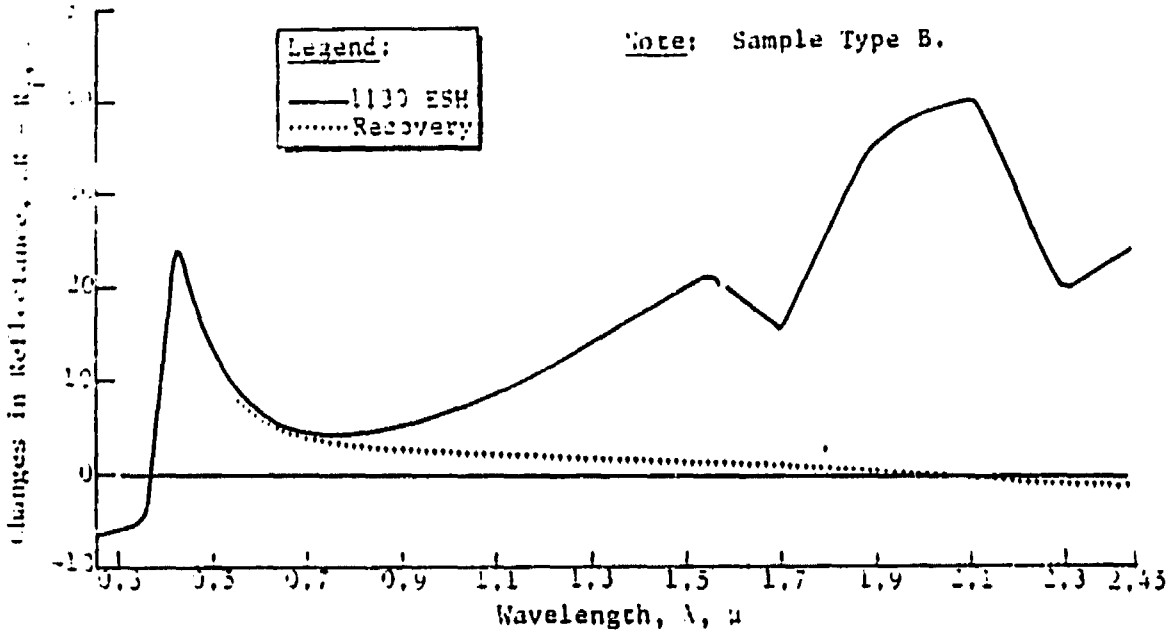
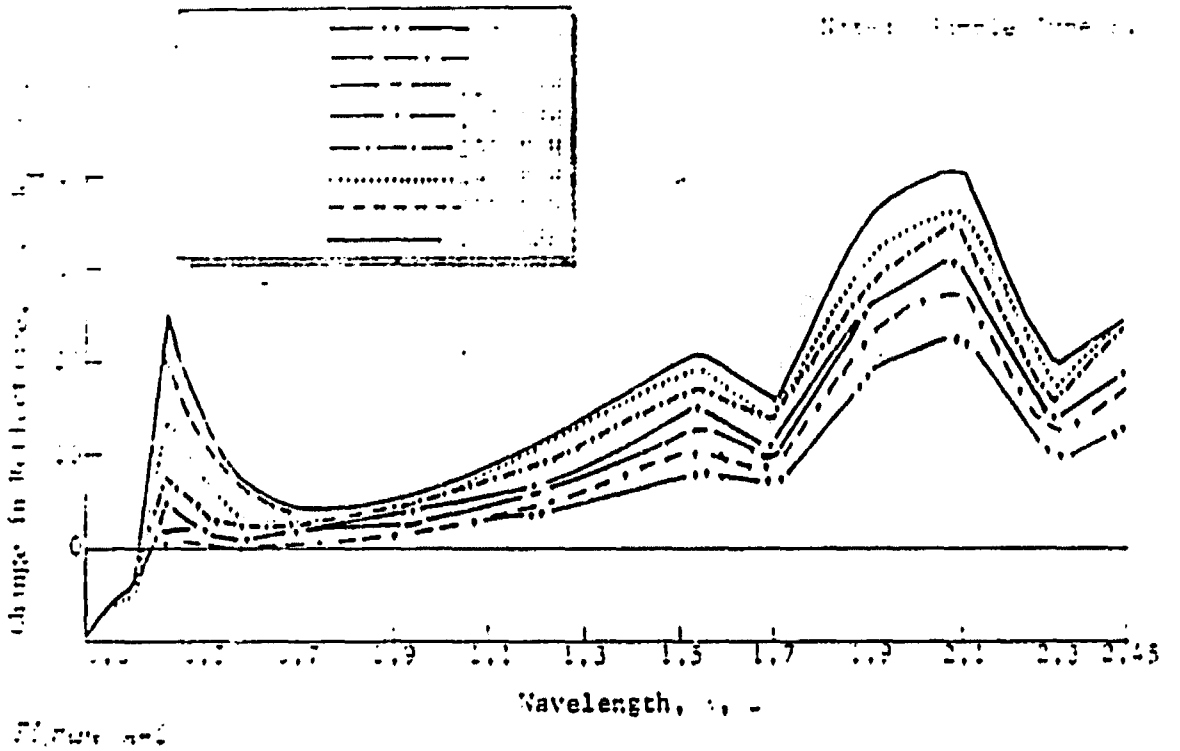


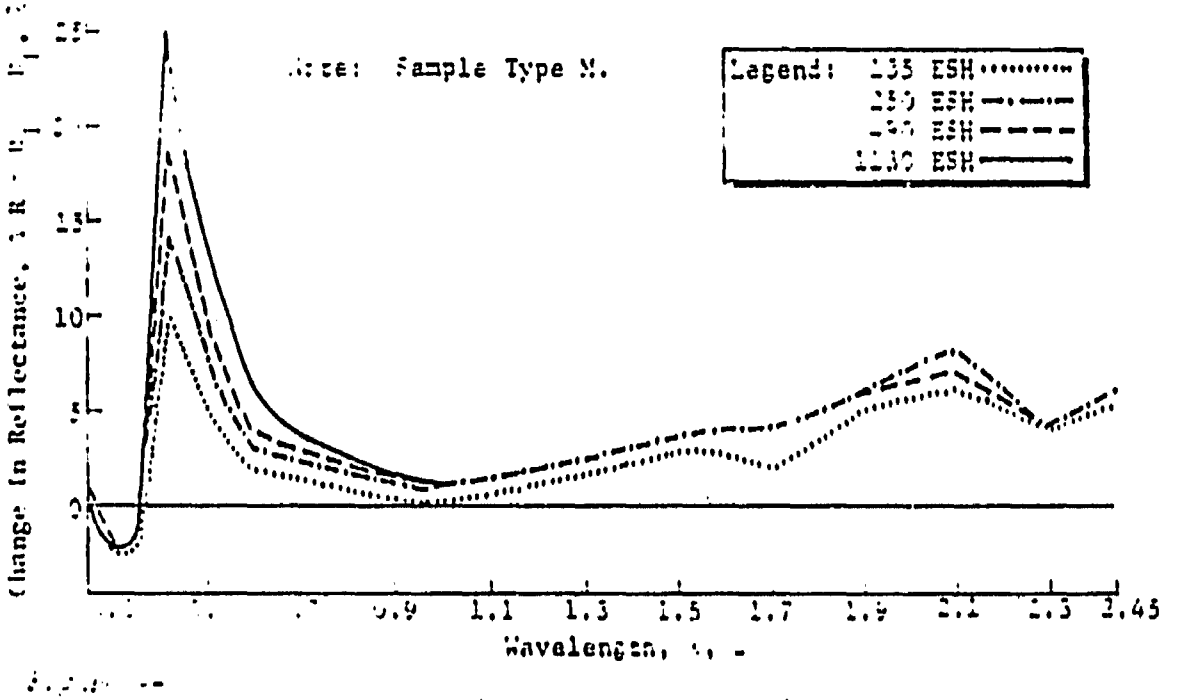
Figure A-1
Reflectance Recovery of S-13 in Air as a Function of Wavelength Following Exposure to Ultraviolet Radiation

Table A-1 Changes in α_s Under Solar Radiation

S-13 Type			
Hours	$\Delta\alpha_s$	Flight	Ref
2000	0.12	OSO-II	9
2400	0.14	OSO-III	7
2040	0.284	Skylab D024	11
700	0.11	Lunar Orbiter II	12
800 ESH	0.8	Lab (IITRI)	12
1330	0.10	Lab (LMSC)	12
1098 at 18 Suns	0.61	Lab (IITRI)	12



Wavelength, λ, μ



Degradation rate studies of the infrared reflection with S-13 showed[13] that the rate increases as the incident radiation decreases from 3500 to 2200 A. With 2600 ± 200 A radiation, the rate is proportional to $\sqrt{I} + 1$. The effect of total dose is not constant but is affected independently by intensity and time.

Some other laboratory and flight data are presented in Table A-2 for S-13G-type coatings. For the Skylab results, the same contamination comment holds here as for the S-13 results in Table A-1.

Table A-2
Changes in α_s Under Solar Radiation

S-13G			
Hours	$\pm\alpha_s$	Flight	Ref
2400	0.07	OSO III	5
2040	0.237	Skylab D024	8
900	0.14	Lunar Orbiter I	9
600	0.09	Lunar Orbiter II	9
1300 ESH	0.8	Lab	9
600	0.01	Lab	

b. Electron Irradiation - The boeing group[10] found that over wide ranges of fluxes and fluences (4×10^6 to 1.7×10^{12} electrons/cm^2/s and 10^{13} to 8×10^{15} electrons/cm^2), no irradiation rate effects from 50-keV electrons are evident from in situ measurements of hemispherical spectra reflectance obtained with an integrating sphere reflectometer. Thus to an acceleration factor of 10^3 or so, laboratory exposures of S-13 and S-13G coatings to 50-keV electrons at rates greater than those in space are valid.

After exposure to electron irradiation, both S-13 and S-13G recover reflectance losses when exposed to dry air (Fig. A-4). However, when exposed to 8×10^{15} electrons/cm^2, "permanant" damage remains even days after exposure to air. Figure A-5 shows the early recovery.

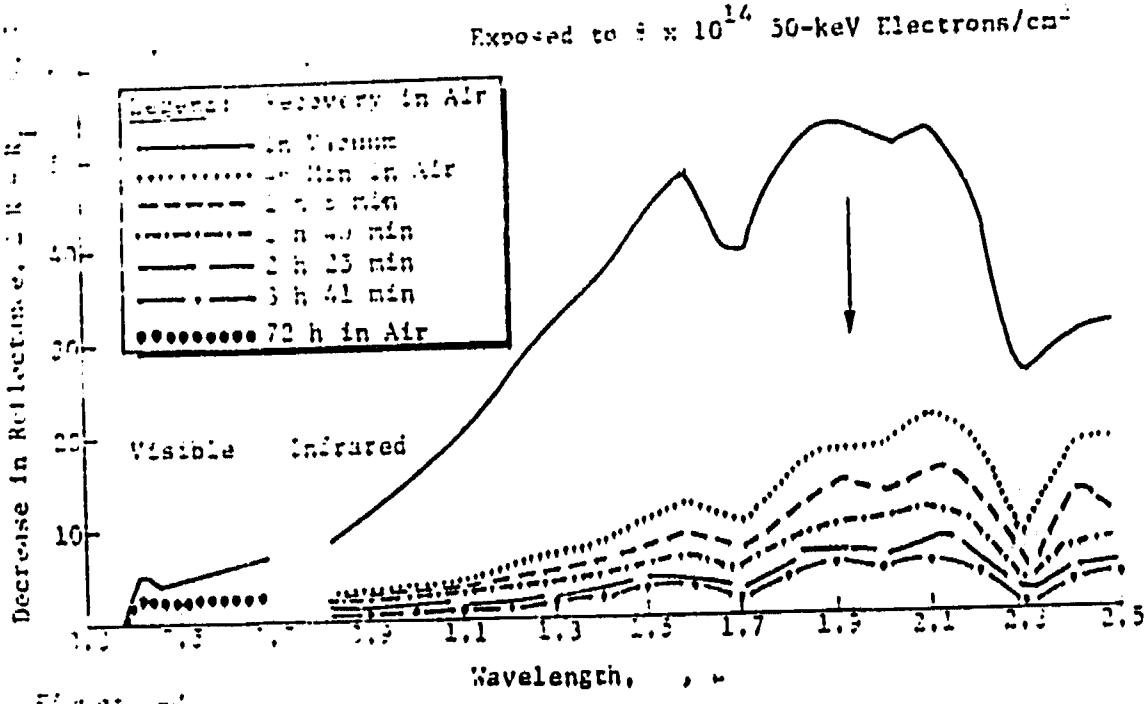


Figure A-4
Spectral Reflectance Changes Due to Electron Exposure and Reflectance Recovery in Air

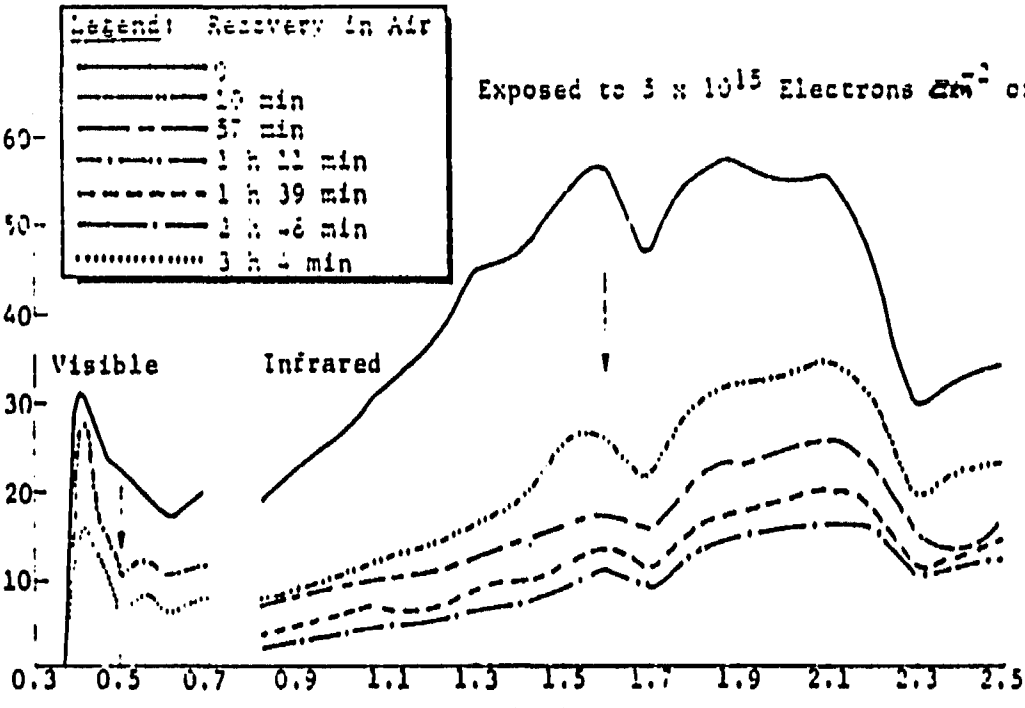


Figure A-5
Postirradiation Reflectance Recovery Properties of S-13G When Revealed to Air

[illegible] Table [illegible] three [illegible] ultraviolet [illegible] ultraviolet followed by electron, and simultaneous ultraviolet and electron. All UV exposures were to 5SH and all electron exposures [illegible] electrons cm^{-2}. Sequential exposures were [illegible] carrier remained in situ in the vacuum exposure chamber.

[illegible] Damage in Polycrystalline CdTe Films

Reflectance after Exposure to	Change in Reflectance at Indicated Wavelengths, %						
	425 nm	491 nm	950 nm	1200 nm	1550 nm	2100 nm	2300 nm
UV Only	1	1	3	6	10	22	14
Electrons Only	1	1	6	11	20	37	24
Ultraviolet followed by Electron	-	-	9	17	30	59	40
Consecutive Ultraviolet and Electron Exposure	1	1	-	7	13	30	19
Simultaneous UV Electron Exposure	0	1	7	12	24	43	30

[illegible] first exposed to electron and then to ultraviolet re[illegible] [illegible] recovery, however, the effect of ultraviolet [illegible] additional effect [illegible] the reflectance beyond the losses [illegible] due to the electron exposure [illegible] the [illegible] reflectance in the ultraviolet region [illegible]

[illegible] to quantify the rate of [illegible] rate of electron and ultraviolet radiation. CdTe was exposed to a low ultraviolet-ion rate (total exposure time 4.1 hours). Simultaneously, it received a fluence of 3×10^{16} electrons/cm^2 programmed so about 90% occurred during the first hour of ultraviolet exposure, and the remaining 10% during the final 3.1 hours of ultraviolet exposure. The spectral reflectance was measured after the first hour. Measurements made after the complete exposure of 4.1 hours show evidence of reflectance recovery (Fig. 4-7).

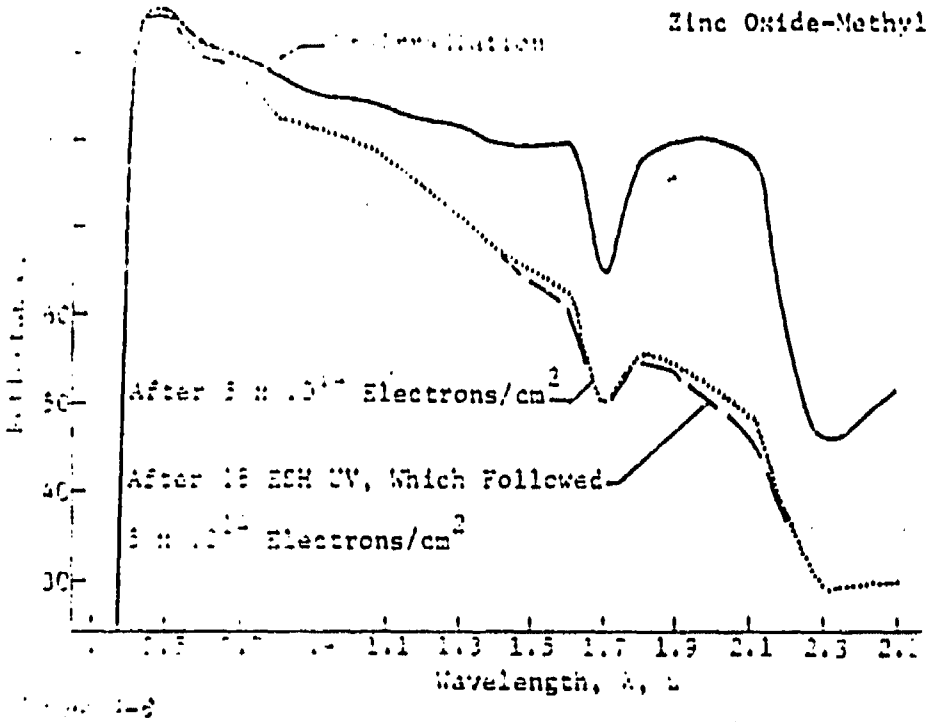


Figure A-[illegible] Spectral Reflectance of S-13 Following Consecutive Exposure to 30-keV Electron Irradiation and to Ultraviolet Radiation (Ref. 10)

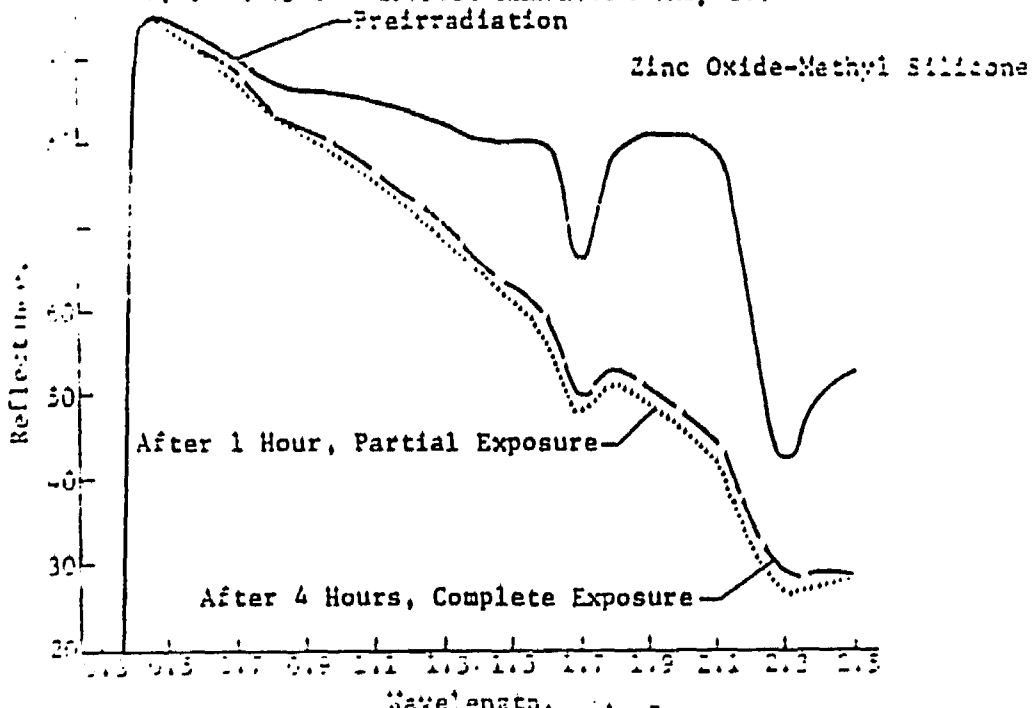


Figure A-[illegible] Spectral Reflectance of S-13 and Effects of Charging the Electron Irradiated Exposure Area Midway Through Test (Ref. 10)

d. Proton and Combined Proton UV Radiation - Changes in α_s in simulated solar wind proton, simulated solar ultraviolet irradiation, and the combined environment are shown[12] in Table A-4. In the combined environment at fluxes below 3×10^{16} protons/cm^2 and less than 1000 sun hours there is less total change than in the ultraviolet alone.

Irradiation with 20-keV protons of S-13G showed[10] that it sustains severe degradation of reflectance in the visible after exposure to 10^{16} protons/cm^2. However the threshold for damage was in the 10^{14} protons/cm^2 range, and even at 10^{15} protons/cm^2 the reflectance degradation was moderate. The buildup of damage and the extent of recovery in air following exposure are shown in Figure A-8. Only partial recovery of reflectance occurs in air.

e. Summary - Wavelength regions in which the largest reflectance changes occur are substantially different for ultraviolet, electron, and proton radiation. Exposure to electrons causes the greatest reflectance losses in the infrared. Ultraviolet radiation and proton radiation result in more damage at shorter wavelengths, particularly at any existing ultraviolet absorption edge.

Table A-4
Changes in Solar Absorptance of S-13 in Simulated Solar Wind Protons and Ultraviolet Radiations[4]

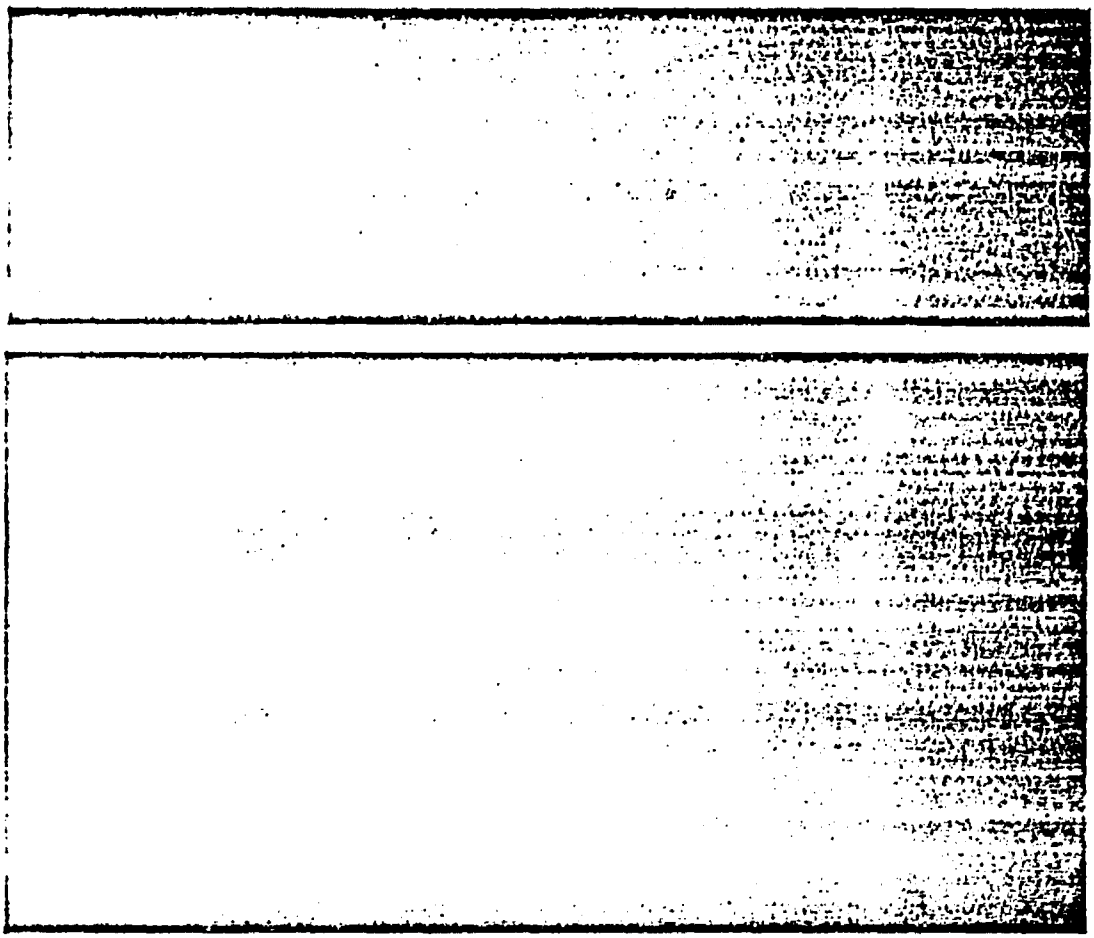


Figure A-8 Buildup of 20-keV Proton Damage in S-13G (Ref 10)

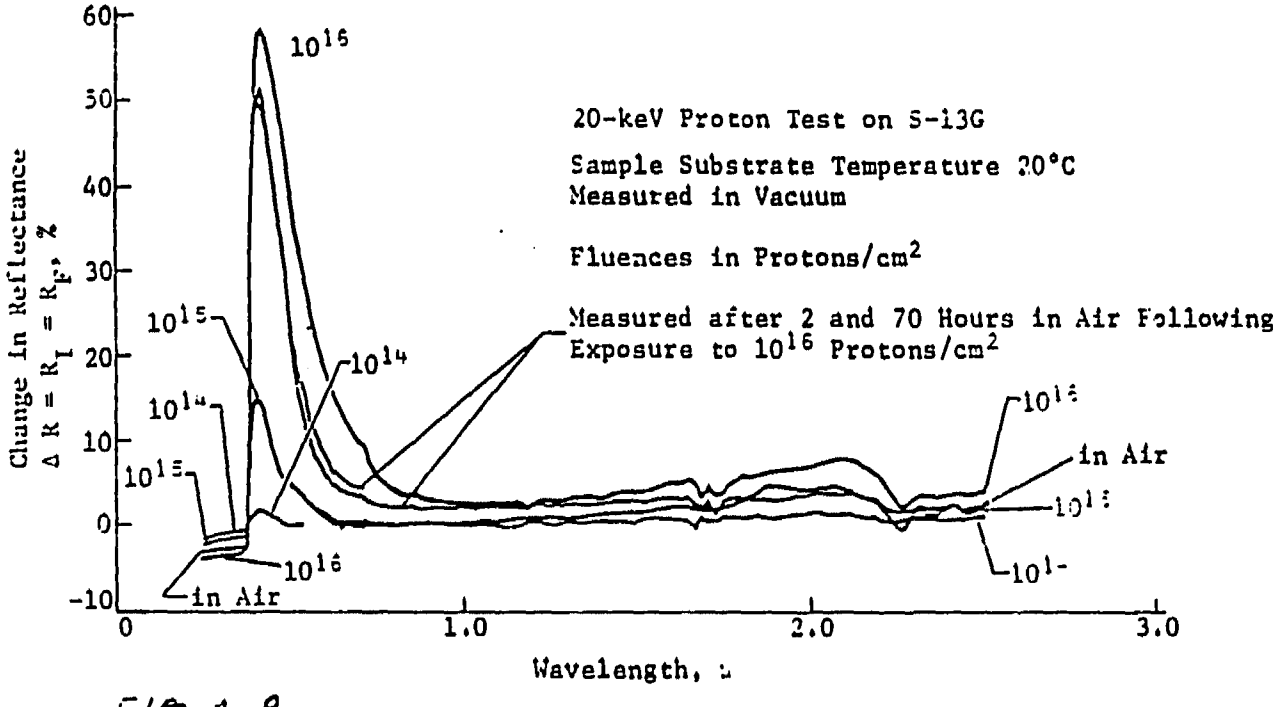

20-keV Proton Test on S-13G
Sample Substrate Temperature 20°C
Measured in Vacuum
Fluences in Protons/cm2
Measured after 2 and 70 Hours in Air Following Exposure to 10^16 Protons/cm2
Change in Reflectance
Δ R = R_I = R_F, %
Wavelength, μ
in Air
in Air

FIG A-8

Material	Proton Exposure		Ultraviolet Exposure		UV and Proton Exposure	
	Simulated Protons/ cm^2 at 2000-eV Energy	Change in Solar Absorptance, %	Ultraviolet Sun-Hours (18-Sun Intensity) +	Change in Solar Absorptance, %	UV Sun-Hours and Protons/cm^2	Change in Solar Absorpta %
S-13	0.43×10^{15}	5.6	90	44.0	$90/0.28 \times 10^{16}$	33.3
	1.3×10^{15}	11.0	432	56.0	$432/1.1 \times 10^{16}$	50.0
	3.0×10^{16}	56.0	1098	61.0	$1098/2.8 \times 10^{16}$	106.0

* Measurements of absorptance of materials at 0.5 - 1.8 μ in vacuum of 10^{-7} torr.

+ Intensity corresponds to 18 times the solar ultraviolet (2200 - 4000 A) intensity at distance of earth in space at zero air

TABLE B-6

[illegible]

[illegible] combined environment exposures to more [illegible] [illegible] [illegible] significantly alters the resulting [illegible] [illegible] effects must be considered in [illegible]

[illegible]

This section first presents information concerning "untreated" materials and then data for metalized films.

[illegible] Teflon and Kapton

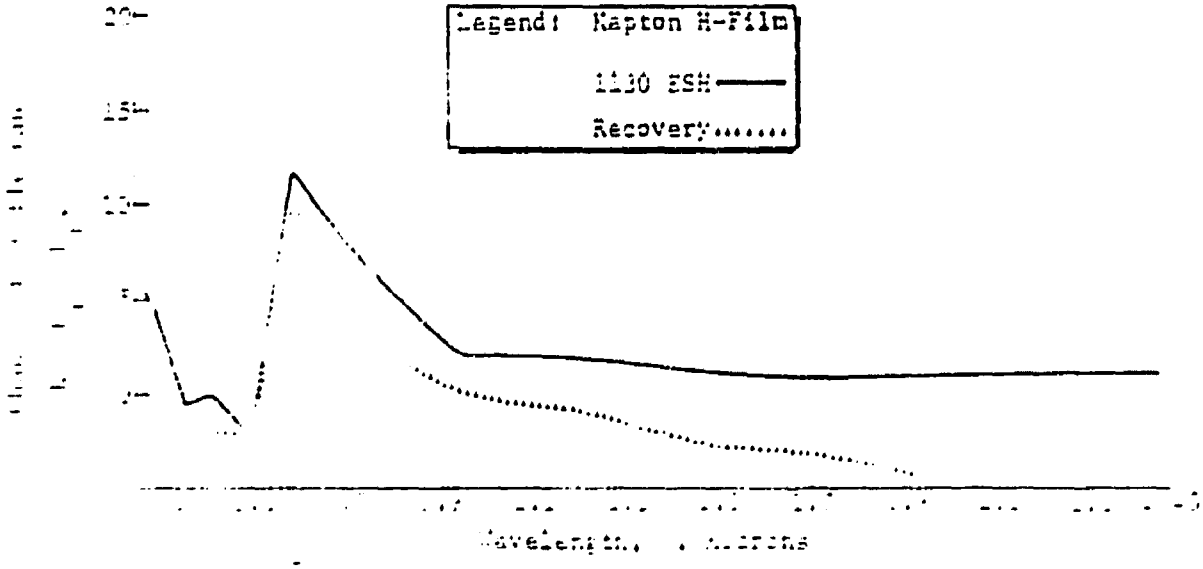
[illegible] Thermal Degradation - Thermal degradation under vacuum [illegible] [illegible] simple first-order kinetics. Decomposition begins near [illegible] with activation energies[4] of 70 to 80 kcal for Teflon and about [illegible] kcal for Kapton. Pertinent pages from Reference 4 are tabulated. These include mass spectral data as a function of temperature.

[illegible]	Pages (inclusive)
Kapton H Film	F1 1 - F15
Teflon Lacing Tape	T1 - T6
Teflon Sheet TFE	T7 - T10
Teflon Tubing FEP	T11 - T14

[illegible] for Teflon is from [illegible] to [illegible] and for Kapton [illegible] The [illegible] range for Teflon is from [illegible] to [illegible] [illegible] for Kapton.

[illegible]

[illegible] Teflon - Teflon [illegible] with the [illegible] described shows some reflection losses, but the [illegible] [illegible] with some increases and decreases in the visible and [illegible] regions. Recovery in dry air[4] is shown in Figure [illegible]. It can be seen that in the IR the in-air reflectance values are about [illegible] greater than than the in situ values.



however, another investigation[14] found there was no effect on the transmission of Kapton (1.5 mil) after 9500 ESH with a source of high and low-pressure mercury arcs, irradiation being under vacuum at 310°. Transmission tests extended over the range from 350 to 750 mm. Teflon (1.5 mil) suffered only a mild degradation (~ 10%) over the same parameters.

Electron Irradiation - Under electron irradiation Kapton showed[10] some reflectance losses but serious degradation occurred only at the highest fluences. Table A-5 shows the reflectance changes at 590 nm.

Table A-5
Decrease in Reflectance at 590 nm For 60-KeV Electrons (Ref. 10)

Exposure, electrons/cm^2					
1×10^{13}	1.6×10^{13}	2×10^{14}	5.5×10^{14}	8×10^{14}	8×10^{15}
0	1	4	13	9	60

With 1-MeV electrons both Kapton and Teflon were unaffected[14] up to 2.6×10^{17} electrons/cm^2.

Proton Irradiation - With 800-keV protons both Kapton and Teflon were unaffected[14] up to 10^{14} protons cm^{-2}.

c. Physical Property Changes

Electron Irradiation, Mechanical Properties - Changes in Teflon induced by irradiation have been assessed by measuring the tensile and flexural characteristics before and after electron irradiation under vacuum.[15] These properties were measured in air. The irradiations were carried out with a Van de Graff accelerator that produced a continuous beam of electrons.

Samples were irradiated to doses up to 10 Mrad at a rate of 345 rad/s, and measurements of mechanical properties were made after approximately 24 hours in air. Figure A-10 shows that both the tensile and flexural modulus increase with dose to approximately the same extent.

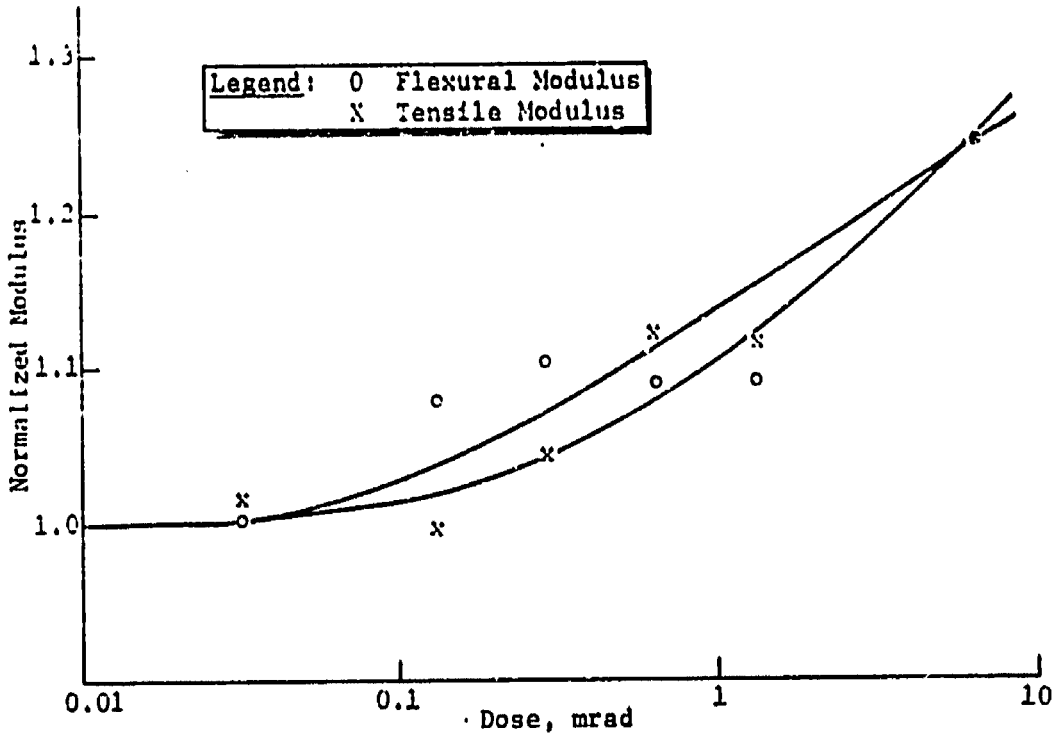


Figure A-10
Flexural and Tensile Moduli As a Function of Dose (16)

Figure A-11 shows the changes in tensile strength and extension. Samples irradiated to a dose of 1 Mrad with 1-MeV electrons at dose rates ranging from 50 to 7×10² rad/s showed that the dose rate has no effect on the resulting change in mechanical properties. Varying the electron energy between 0.4 and 1.6 MeV showed the mechanical properties to also be independent of the electron energy. For comparison, data on strength and dose from an unclassified portion of a classified report[16] are also included in Figure A-11. It can be seen that the low-energy irradiations appear to behave in a similar manner.

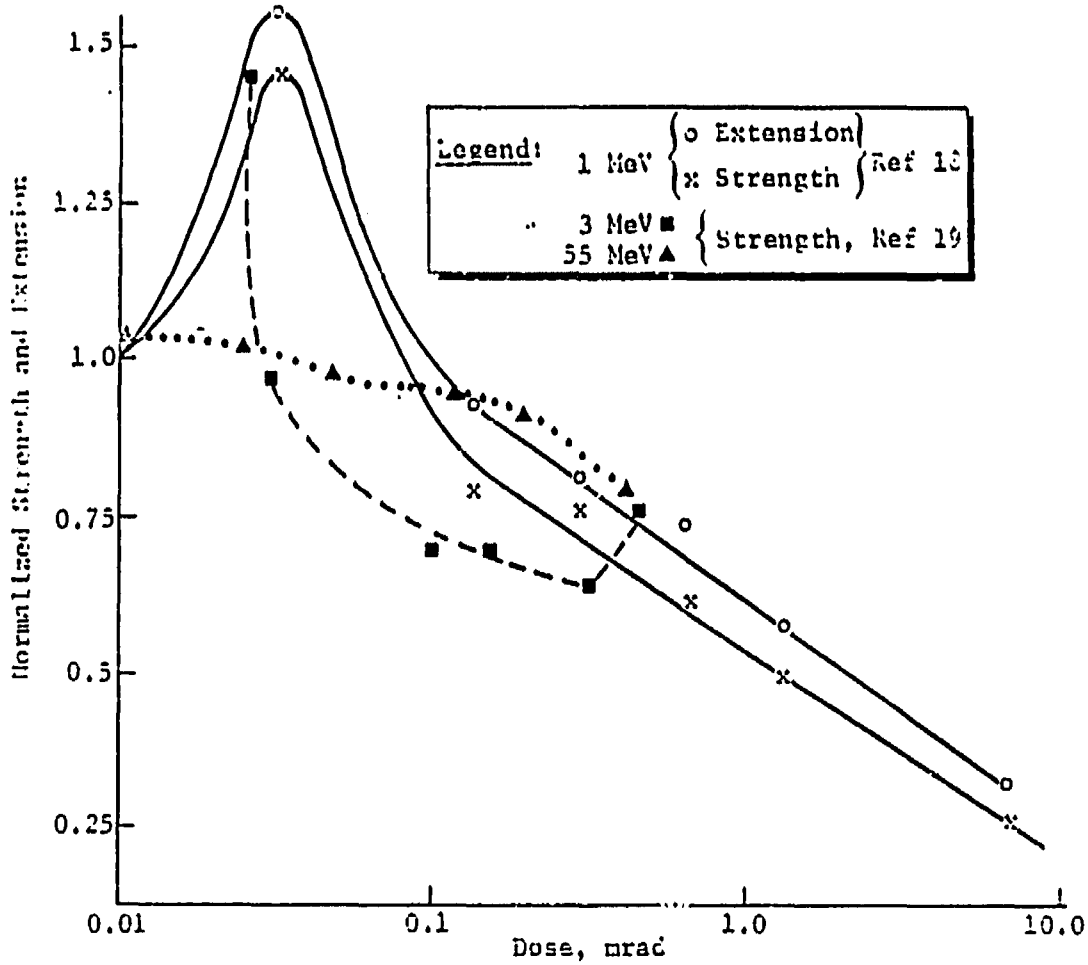


Figure A-11
Tensile Strength and Extension to Failure (Ref 18) and Tensile Strength at 60% Elongation as a Function of Dose (Ref 18)

Electron Irradiation, Electrical Properties - Changes in electrical properties of Teflon after electron irradiation have been obtained from unclassified portions of Reference 18. Although the irradiations were done at 22°C and 760 torr, the results are included here for completeness. Table A-6 shows the changes in electrical conductivity as a function of dose with 3- and 55-MeV electrons, and Table A-7 shows the changes in the dielectric constant.

Table A-6
Pre and Postirradiation Conductivity at Electric Field of 20 V/mil*

Electron Energy, MeV	Material	Nominal Dose, rads-Teflon					
		2×10^4		1×10^5		5×10^5	
		Pre	Post	Pre	Post	Pre	Post
3	1	<1.4	1.7	<1.7	1.8	1.7	1.9
	2	1.6	1.5	1.5	1.8	1.6	2.1
	3	<1.3	<1.3	<1.4	1.5	<1.6	4.2
55	1	<1.3	2.4	<1.3	1.9	<1.3	2.4
	2	<1.3	2.0	<1.3	1.8	<1.3	2.1
	3	<1.8	2.4	2.8	4.2	<1.3	2.2

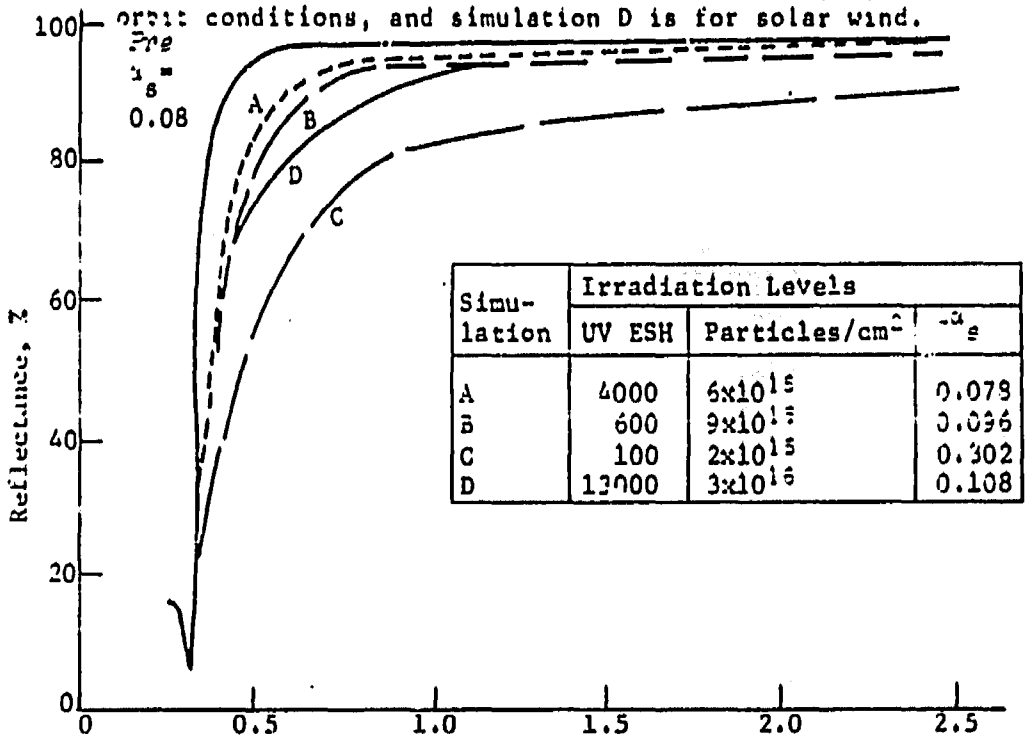
* Materials: 1 - TFE-7; 2 - TFE-6C; 3 - FEP-100.
Units of conductivity, 10^{-17} $(\text{ohm-cm})^{-1}$.
All values average of three samples.

Table A-7
Percentage Change in Dielectric Constant As a Function of Frequency and Absorbed Dose (22°C, 760 torr)

Electron Energy, MeV	Frequency, Hz	Material*	Nominal Dose, rads - Teflon		
			2×10^4	1×10^5	5×10^5
3	10^2	1	-4.11	-3.31	-4.39
		2	-4.21	-3.02	-3.10
		3	-2.50	-0.98	+1.02
	10^3	1	-4.06	-3.31	-3.10
		2	-4.19	-3.02	-3.10
		3	-2.55	-0.98	+1.01
	10^4	1	-4.03	-3.28	-2.97
		2	-4.19	-3.01	-3.08
		3	-2.56	-0.99	+1.00
	10^5	1	-4.03	-3.27	-3.03
		2	-4.17	-2.98	-3.06
		3	-2.57	-1.02	+0.98
55	10^2	1	+0.25	+0.69	+1.27
		2	-2.30	-2.84	-3.85
		3	-2.80	-1.52	+0.22
	10^3	1	+0.03	-0.57	+0.39
		2	-0.79	-2.85	-3.59
		3	-3.06	-1.68	-0.06
	10^4	1	-0.27	+0.47	+0.49
		2	-2.45	-3.42	-3.84
		3	-3.04	-1.75	-0.65
	10^5	1	-0.34	+0.55	+0.46
		2	-2.33	-3.45	-3.84
		3	-3.15	-1.57	-0.36

* Material: 1 - TFE-7; 2 - TFE-6C; 3 - FEP-100.

Simultaneous UV and Particle Irradiation, Optical Properties - Figure A-12 shows[17] the effects of sumultaneous irradiation on the solar absorptance of 5-mil FEP Teflon. Simultions A, B, and C are for earth orbit conditions, and simulation D is for solar wind.



Simulation	Irradiation Levels		
	UV ESH	Particles/cm^2	α_s
A	4000	6×10^{15}	0.079
B	600	9×10^{14}	0.096
C	100	2×10^{15}	0.302
D	13000	3×10^{16}	0.108

Figure A-12 Effects of UV, Electrons, and Protons on 5-mil FEP Teflon (Ref. 17).

Simulation A is at a UV irradiation rate of one-sun plus charged particles (electrons and protons) at rates of 2×10^8 (e + p) $cm^{-2}s^{-1}$. Simulation B considers a smaller fraction of a year orbital time with magnetic substorm conditions, i.e. one-sun UV plus electrons and protons at a rate of 2×10^9 (e + p) cm^{-2} s^{-1}. Simulation C has fluxes increased to peak orbital values of 3×10^9 electrons cm^{-2} s^{-1} and the same flux for protons. The originally transparent film becomes translucent or even opaque with irradiation. A simulated solar wind is given as Simulation D with a flux of 1×10^{10} protons cm^{-2} s^{-1} combined with UV radiation. With this intensity of irradiation, the Teflon's visual appearance becomes that of a white paint.

A sample of FEP Teflon was flown on Skylab DO24. Transmission losses in the UV-visible were attributed[11] to contamination.

Simultaneous UV and Particle Irradiation, Mechanical Properties - Irradiation with 1-MeV electrons and simulated solar radiation (2.5 kW m^{-2} xenon lamp) indicated[15] that the predominant effect of the UV radiation on mechanical properties will be the influence of the rise in temperature of the sample on the effects of the electron irradiation.

Teflon TFE and FEP samples from Surveyor III were returned[16] from the moon by Apollo XII. Teflon FEP appeared to suffer only a small degradation in tensile strength whereas TFE cable wrap was appreciably degraded with tensile strength decreased by 75% and elongation by 90%.

Results derived[19] from the Skylab D024 experiment are depicted in Figure A-13. It is of interest to compare this figure with the tensile strength data presented in Figure A-11.

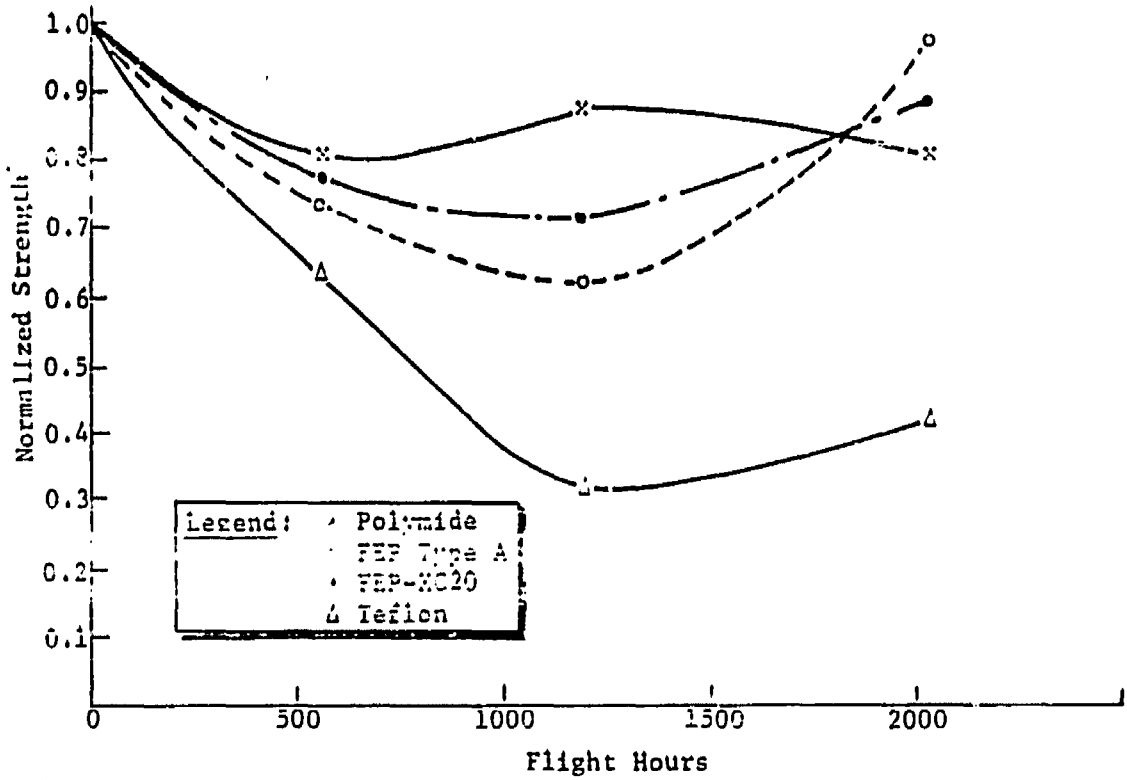
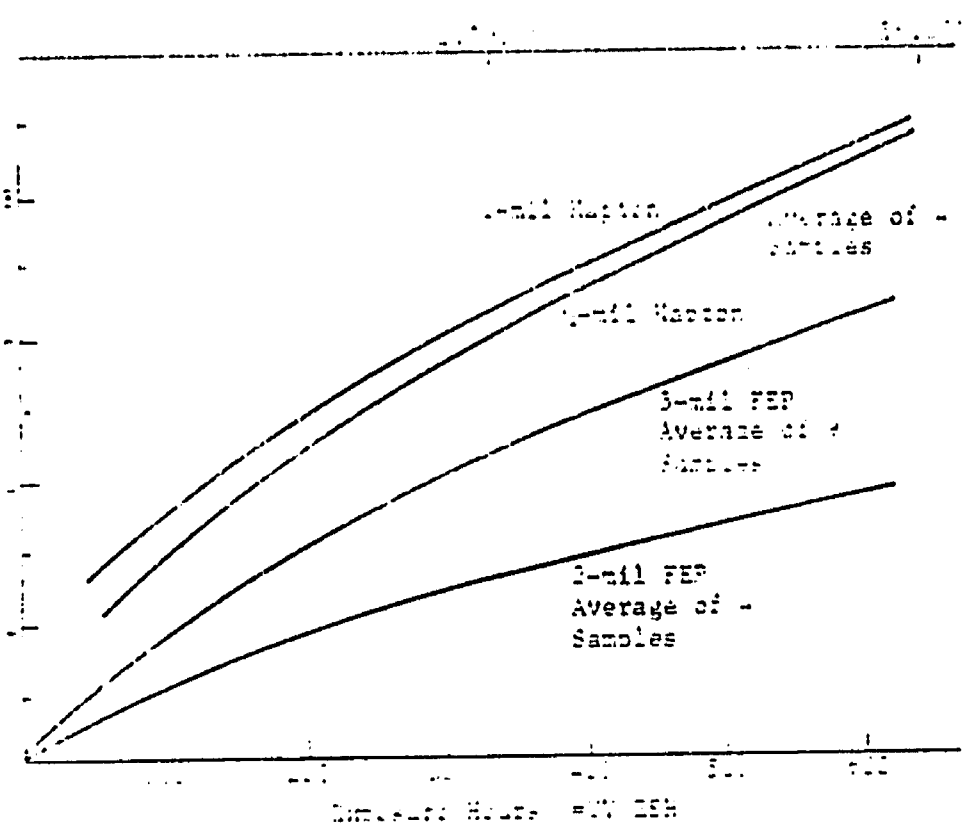


Figure A-13
Tensile Strength As a Function of Time During Skylab D024 Experiment

2. Metalized Teflon and Kapton Films

The survey of these materials under solar simulation is dominated by the extensive studies of Boeing[20] and TRW[21]. The Boeing group studied optical properties up to 9100 ESH, and the TRW group extended the times to years. The TRW group also studied mechanical properties under the same simulation.


5-mil FEP
Average of 4
Samples
2-mil FEP
Average of 4
Samples

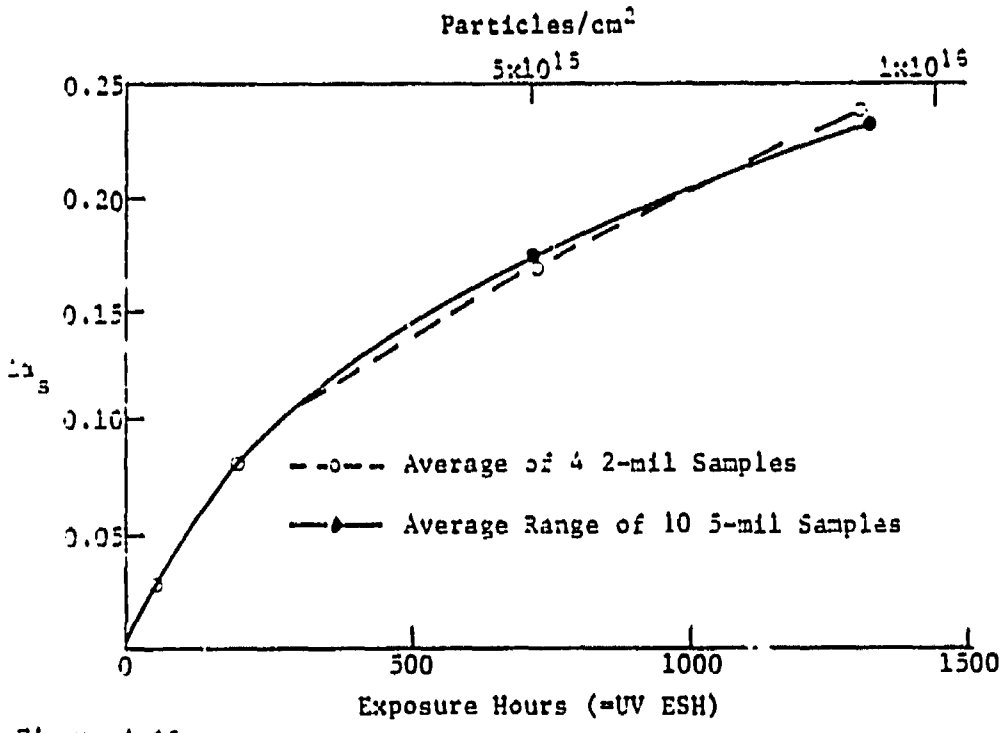


Figure A-15
Solar Absorptance of Metalized 2-mil and 5-mil FEP Films Irradiated by 30-keV Electrons, 20-keV Protons, and UV Equal Fluences of Each Particle (Ref 20)

Similar metalized films were studied for longer times by the TRW group.(21) Figure A-16 was derived from their data. As with the shorter time exposures, the changes in solar absorptance increase with time. Normal emittances, measured in air, after three years of equivalent space exposure remain virtually unchanged.

c. Mechanical Properties - Extensive testing of metalized Teflon and Kapton films was done by the TRW group(21) under near-UV, 30 and 200-keV electrons simulataneously under vacuum. Mechanical properties were tested both in situ and ex situ.

Results indicated that FEP and PFA Teflon materials exhibited brittle behavior after 18 months of equivalent exposure. By a 30-month equivalent exposure, essentially all Teflon materials had experienced a complete loss of elongation. The Kapton materials experienced a 25 to 40% reduction in ultimate elongation but had only small changes in modulus and ultimate strength. No brittle failure occurred during the entire test program. The in situ and ex situ tensile test results were qualitatively consistent (i.e., Teflon exhibited catastrophic degradation in mechanical properties while Kapton exhibited only some degradation), although the rate of degradation for Teflon in the in situ chamber was less than that for the ex situ specimens. This difference suggests that return of irradiated specimens to atmospheric conditions prior to testing may affect the measured properties.

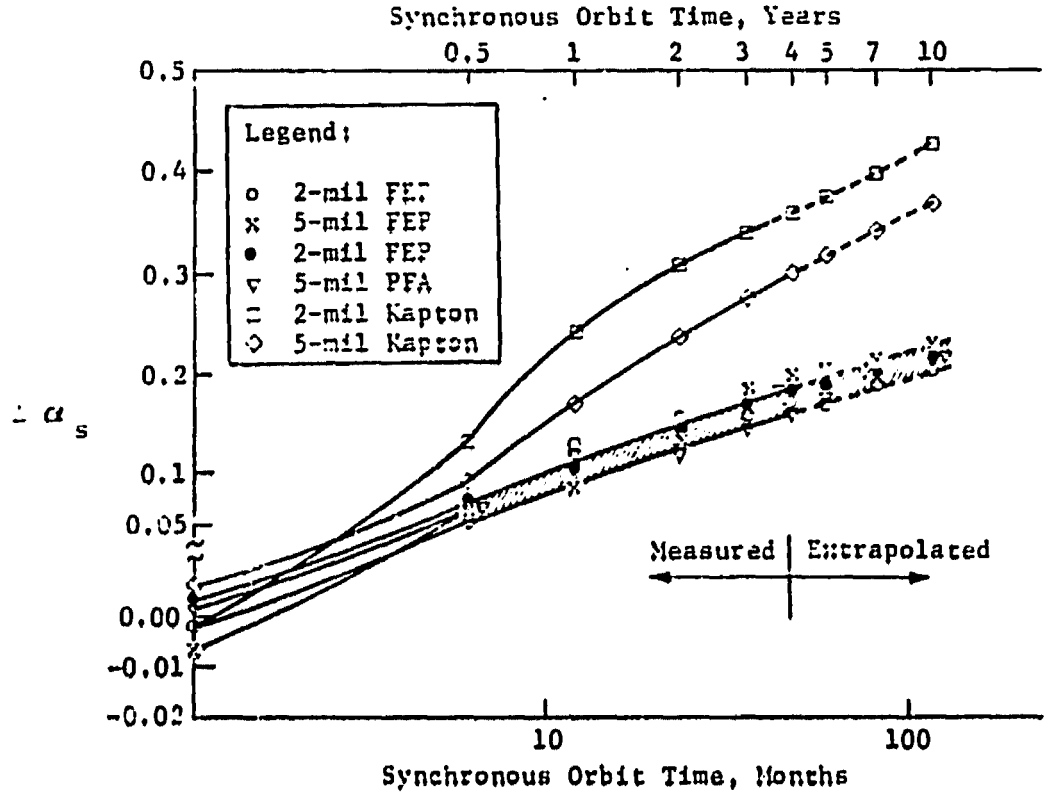


Figure A-10
Changes in Solar Absorptance Characteristics of Metallized Films of Teflon and Kapton as a Function of Time (Radiation: Near-UV and Far-UV, 17-keV Protons 1, 7, 50, and 100-keV Electrons, Points Are Average of 3 Samples Each)

Tensile properties were sensitive to specimen size. Table A-8 summarizes the key results.

Radiation exposures were carried out with 1-inch gage lengths. Table A-9 shows the in situ secant modulus changes under simultaneous UV and 50 and 200-keV electrons.

These results may be compared with the ex situ results presented in Table A-10.

Table A-8 Effect of Tensile Specimen Gage Length on Tensile Properties*

Material	1-in. Gage Length			4-in. Gage Length			Ratios†		
	Modulus, ksi	Ultimate Strength, ksi	Ultimate Elongation, %	Modulus, ksi	Ultimate Strength, ksi	Ultimate Elongation, %	E_u/E_u	σ_u/σ_u	$\varepsilon_u/\varepsilon_u$
20FEPAGIN	66.9	3.1	480.0	89.6	2.1	216.5	1.34	0.66	0.45
30FEPAGIN	57.4	3.5	622.0	75.8	2.8	343.0	1.32	0.80	0.55
20KAL	302.5	23.9	66.5	391.0	20.4	18.0	1.46	0.85	0.27
50KAL	324.0	24.9	75.0	485.0	21.3	25.5	1.50	0.85	0.34

* Average of machine and transverse direction properties, three specimens per main direction.

† E = modulus, σ ultimate strength, ε = elongation, subscripts 1 and 4 represent values for 1- and 4-inch gage lengths, respectively.

Table A-9
In Situ Secant Modulus (E_s) at 8% Strain, ksi*†

Materials	Exposure, Months					
	0	6	12	18	24	30
2-mil FEP	87	85	88	100	103(1.7%)(‡)	
5-mil FEP	77	78	78	84	84	71(1.6%)¶
2-mil PFA	96	97	99	78	96	93(1.9%)¶
2-mil Kapton	343	355	349	352	360	335
5-mil Kapton	341	341	357	393	348	313

* E_s = secant at 8% strain/0.08 in ksi.

† Most Results Average of 2 to 3 Specimens.

‡ ( ) indicates that sample failed at XX% strain.

¶Specimen Identification

2-mil FEP Teflon with Vacuum-Deposited Silver and Inconel

5-mil FEP Teflon with Vacuum-Deposited Silver and Inconel

2-mil PFA Teflon with Vacuum-Deposited Silver and Inconel

2-mil Kapton with Vacuum-Deposited Aluminum

5-mil Kapton with Vacuum-Deposited Aluminum

* (XX%) indicates that sample failed at XX percent strain.

	Exposure, Months					
Materials *	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
3-mil PFA	[illegible]	[illegible]		-	-	
2-mil Kapton	324	353	315		160	
5-mil Kapton	345	360	293		235	

* Tensile tested to failure in air; air exposure duration between 1 and [illegible] minutes.

† Average of 3 specimens in machine direction.

‡ XX% indicates that sample failed at XX% strain.

π Irradiated specimen brittle to the touch; no tensile test possible.

Tensile properties under these exposures are presented in Tables A-11 and A-12.

*Table A-11 In Situ Tensile Properties at Failure**

	Elongation, %			Tensile Strength, psi		
	Exposure, Months					
Materials*	0	9	39	0	9	39
2-mil FEP	473	45		3470	2500	
5-mil FEP	650	105†		3660	2200†	
5-mil PFA	659	55	109	4725	2440	2240
2-mil Kapton	68		35	24750		23350
5-mil Kapton	91		60	2720		26800

* Most results average of 2 specimens.

† No failure; stress and elongation at maximum head travel of testing equipment.

Ee Film Tensile Properties at Ambient *,-

Material	Exposure, Months											
	Elongation, %						Tensile Strength, psi					
	0	6	12	17	30	36	0	6	12	17	30	36
2 mil FEP	[illegible]	[illegible]	2.*	1.5	‡	‡	3470*	2150	1985*	‡	‡	‡
5 mil FEP	6-8	7	13	4.8	‡	‡	3660	1900	1890	1690	‡	‡
5 mil PFA	60.	9	13-	‡	‡		4-20	2000	2060	‡	‡	
2 mil Kapton	68	80	73				24750	26600	27000		26500	
5 mil Kapton	91	80	80				27200	30400	28300		26400	

* Most results average of 3 specimens.
- Tensile tested to failure in air; air exposure duration between 1 and 20 minutes.
‡ Irradiated specimen brittle to the touch; no tensile test possible.
* Samples failed at 4% Strain.

Table A-II

Conclusions

Some conclusions that may be drawn from these results are as follows. The use of Teflon materials for thermal control purposes or in applications requiring flexibility after exposure is not recommended for space. Kapton materials experienced a coupling in δ_s, became black, and exhibited a 35 to 40% reduction in ultimate elongation, a slight reduction in tensile strength, and a negligible change in modulus. These changes, however, are not deemed catastrophic enough to eliminate its continued use in space systems.

Critical optical and thermostructural properties for Teflon and Kapton are primarily due to low-energy proton radiation and/or its synergistic combination with other environmental components.

The discoloration of Teflon and Kapton is limited to the upper layer of exposed material. Light scratching of the surface removes the discoloration, revealing clear material underneath. This result supports the contention that protons are the primary cause of the optical degradation [proton penetration depth is less than 0.3 um (~0.01 mil)].

Catastrophic changes in mechanical properties for Teflon are primarily due to near-ultraviolet radiation and/or its synergistic combination with high-energy electrons. Specimens exposed to five-year equivalent electron radiation retain a percentage of their original ultimate elongation, while all specimens subjected to combined near-ultraviolet and high-energy electron radiation become brittle after 17 to 30 months of exposure.

Changes in mechanical properties for Kapton are primarily due to near-ultraviolet radiation and/or its synergistic combination with high-energy electrons. Specimens exposed to five-year equivalent electron radiation show a negligible change in mechanical properties; however, combined near-ultraviolet and high-energy electron radiations result in a measurable, but not catastrophic, reduction in ultimate elongation.

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